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A study on the effect of rotational dynamic characteristics of a machine tool spindle drive on milling processes

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Abstract

A milling operation is inherently an intermittent material removal process where cutter engagement and disengagement is repeated until the end of the material removal process. During the process, the cutter receives multiple impacts and mechanical and thermal vibrations which eventually damage the cutting edge. The optimum rigidity and damping of the spindle motor for the least tool damage highly depends on the cutter and workpiece material properties and the cutting application. This paper introduces the concept of flexible rotational rigidity control using a high performance Permanent Magnet Synchronous Motor (PMSM) which is used as a direct spindle drive. With the PMSM spindle, the spindle rotational characteristics can be adjusted for optimizing the cutting process in order to prevent tools from unwanted premature damage. Simulation models of the spindle motor drive system are presented, which show that a very stiff spindle can be realized by fully utilizing the potential capability of the PMSM and a spindle with the same dynamic properties of a conventionally used induction motor can be realized with a single PMSM spindle. The system prototype and feasibility studies are also presented in this paper. The experimental results show that the PMSM spindle characteristics behave differently depending on the controller setting, and the spindle motor drive system rotational characteristics greatly affect the cutting process, which confirms the importance of the flexible motor control concept.

Keywords: Spindle; Motor; Milling

1. Introduction

A milling operation is inherently an intermittent cutting process which is greatly influenced by the machine and spindle dynamics and they affect on the tool and workpiece during the period of material removal. The rotational rigidity of a spindle system is mainly determined by the spindle shaft mechanical properties and servo rigidity of the motor. When the spindle system is completely rigid, a high impact is applied to the cutting edges. Although it highly depends on the tool and workpiece material properties' fracture mechanics, sometimes the excessive load leads to unexpected tool damage such as chipping wear at the cutting edge. In such a case, it is possible to soften the tool damage by absorbing the impact force in the spindle drive system by lowering the rigidity of the motor. However, in contrast, the lower rotational rigidity of the spindle often causes poor cutting quality, unstable cutting processes, and vibrations for certain tool and workpiece materials. Thus, it is preferable to keep high rigidity of the overall cutting process for some machining applications. Machine tools are used to cut a wide variety of workpieces by different kinds of tool shapes and materials, and thus flexibility to meet a variety of requirements by users is essential for machine tools. Therefore, it is important that the spindle rotational dynamics can be easily adjusted, allowing for optimal spindle settings for the suitable cutting process to be selected depending on the tool type, workpiece materials, and the application.

Since achieving flexible dynamics by changing the mechanical properties is not a practical approach, it should be achieved by the software control of the spindle drive system. To control the spindle characteristics by software, the motor should have the highest dynamic

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performance possible. Such a high bandwidth spindle motor was developed in past studies by authors [1]. It was reported that induction motors conventionally used for machine tool spindles are not appropriate to achieve a high bandwidth due to inherent characteristics of the drive principle. The developed spindle equips a Permanent Magnet Synchronous Motor (PMSM) which has the advantage of achieving a high bandwidth.

To prevent unwanted vibration, many researchers have conducted in depth studies [2, 3]. Because of this, chatter stability is now reasonably predicted and has been practically applied in many shop floors. However, few people have addressed the influence of the dynamic characteristics of the spindle rotational direction even though the vibration directly influences the relative motion between the cutting edge and workpiece, which essentially realizes a material removal process. The previous study by authors [1] indicates that the spindle rotational dynamics is also important for determining the cutting process. While the chatter stability concept focuses on unstable cutting processes, this study focuses only on optimizing the cutting process under stable milling operations. This paper introduces the concept of the flexible spindle control, its effect on cutting processes, and an example by mathematical model and actual experimentation.

2. Dynamic characteristics of PMSM and induction motor used for this study

The spindle system developed in past studies in industry [1] was installed on a Mori Seiki NV7000, a high rigidity vertical CNC machining center. Fig. 1 shows a Bode plot of the high performance PMSM experimentally obtained by swept-sine analysis using a dynamic signal analyzer. Fig. 2 also shows a Bode plot of an induction motor which was originally installed on the machine and whose size is almost the same as the PMSM. While the bandwidth of the PMSM is approximately 470Hz, 107 Hz is the highest for the induction motor. It is obvious that a wider range of spindle motor adjustment is possible with the PMSM when compared to its induction driven counterpart.

3. Models for variable dynamics software control

As stated earlier, it is important to let the machine tool spindle have flexible dynamic characteristics by software control. Different dynamic settings can be used to optimize milling process depending on the specific milling application. To implement a flexible software control, the system models for the PMSM and a motor dynamic model to be achieved should be developed and the motor parameters must be identified. From the equivalent circuit of the PMSM [4], the synchronous motor can be modeled as:

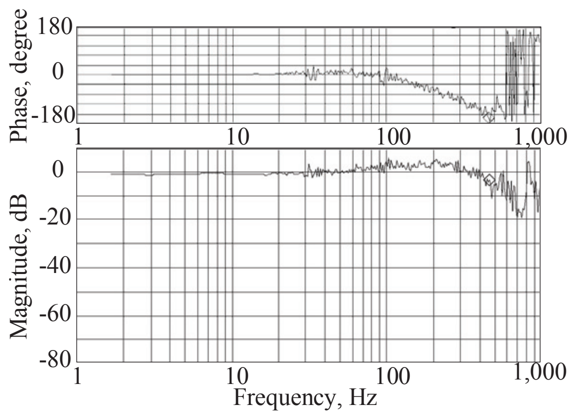

Fig. 1. Bode plot of the PMSM (bandwidth 470 Hz).

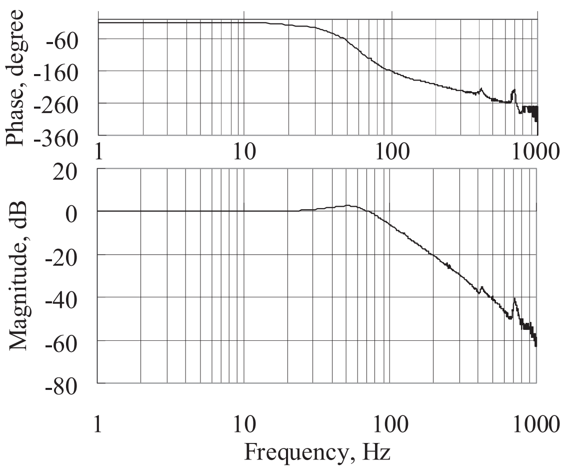

Fig 2. Bode plot of the induction motor (bandwidth 107Hz).

$$PMSM = \frac{1}{R_{PMSM} + L_{PMSM}s} \qquad (1)$$

where, R_{PMSM} and L_{PMSM} are the resistance and inductance of the PMSM, respectively.

From the PMSM model, the transfer function $G_{PMSM}(s)$ for the current feedback system becomes:

$$G_{PMSM}(s) = \frac{K_{ao}}{L_{PMSM}s + R_{PMSM} + K_{ao}} \qquad (2)$$

where, K_{ao} is the current control gain of the PMSM.

Similarly, an induction motor model and the transfer function of the current feedback system for the induction motor $G_{IM}(s)$ can be obtained as:

$$IM = \frac{R_r + L_r s}{(L_s L_r - M^2)s^2 + (R_s L_r + R_r L_s)s + R_s R_r} \quad (3)$$

$$G_{IM}(s) = \frac{K_a (R_r + L_r s)}{(L_s L_r - M^2)s^2 + (R_s L_r + R_r L_s + K_a L_r)s + R_r (R_s + K_a)} \quad (4)$$

where, K_a, R_s, R_r, L_s, L_r, and M are current control gain, stator resistance, rotor resistance, stator inductance, rotor inductance, and mutual inductance of the induction motor, respectively.

To demonstrate the flexible dynamics control, the dynamics of the induction motor introduced in the previous section are simulated with the PMSM model because dynamics of an induction motor are sometimes preferable for cutting applications rather than the PMSM. From the feedback systems (2) and (4) and Bode plots in Fig. 1 and 2, the system parameters were identified. The simulated responses for the PMSM and the induction motor were illustrated by the dashed and solid lines of Fig. 3. Using the motor models, it is possible with the PMSM spindle to realize the same dynamic characteristics of the induction motor spindle by introducing a function $G_{comp}(s)$ in the controller as a compensator. The compensator can be written as:

$$G_{comp}(s) = \frac{K_a K_{IM} G_{IM}(s)}{K_{a0} K_{PMSM} G_{PMSM}(s)} \quad (5)$$

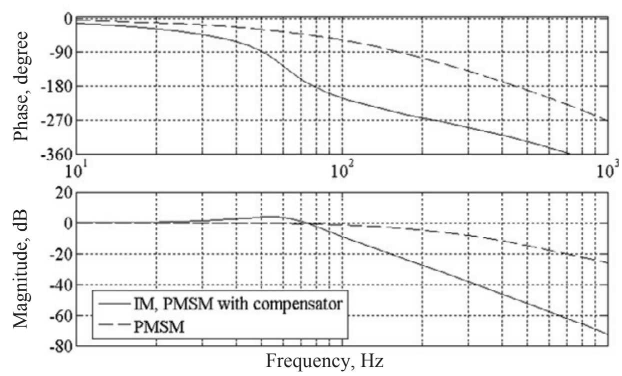

Fig. 3. Simulation of the frequency response of motors.

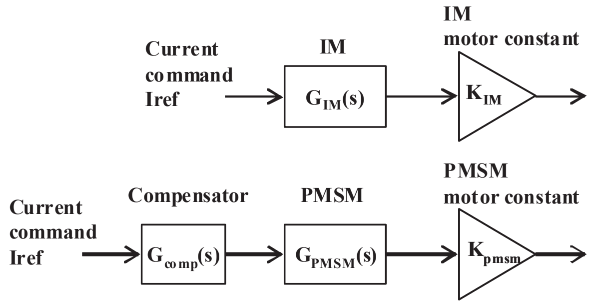

Fig. 4. IM and PMSM with compensator current control models.

where, K_{PMSM} and K_{IM} are motor constants of the PMSM and induction motor, respectively.

The block diagrams illustrating the induction motor current control model and the PMSM with the compensator are shown in Fig. 4. From the diagrams and the transfer functions, it is obvious that the Bode plot of the PMSM with the compensator becomes theoretically the same as the one of the induction motor. In Fig. 3, the Bode plot for the PMSM with the compensator is overlapped with the one for the induction motor.

Although the transfer function of the induction motor was used for this simulation, different kinds of motor models and parameters can be chosen. Therefore, a variety of dynamic characteristics can easily be achieved with the high performance PMSM by freely changing the compensator G_{comp} in the controller.

4. Feasibility study

A cutting experiment has been conducted by changing the rotational dynamic characteristics of the PMSM spindle as an example of the effect on the cutting process. As the compensator model has not been implemented in the driver of the PMSM, the velocity loop gain of the motor is tentatively adjusted to simulate different dynamics. In the experiment, C55 carbon steel was used as the work material. Coated tungsten carbide tools (ISO P grade) with a face mill diameter of 160 mm were used for dry down milling operations. Table 1 shows the cutting conditions used for the experiment.

Table 1. Cutting conditions for the milling test.

Cutter		Speed		Feed		
Diameter	Number of teeth	Spindle Rotational Speed	Cutting Speed	Feed per tooth	Depth of cut	Width of cut
D	z	N	V	f	d	W
mm		rpm	m/min	mm/tooth	mm	mm
160	6	500	250	0.5	3	100

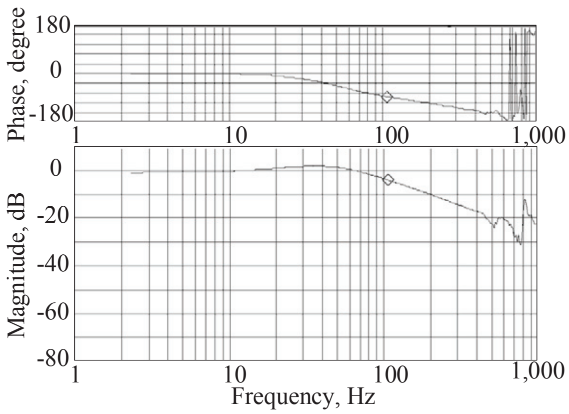

Fig. 5. Bode plot of the PMSM after detuning (bandwidth 100 Hz).

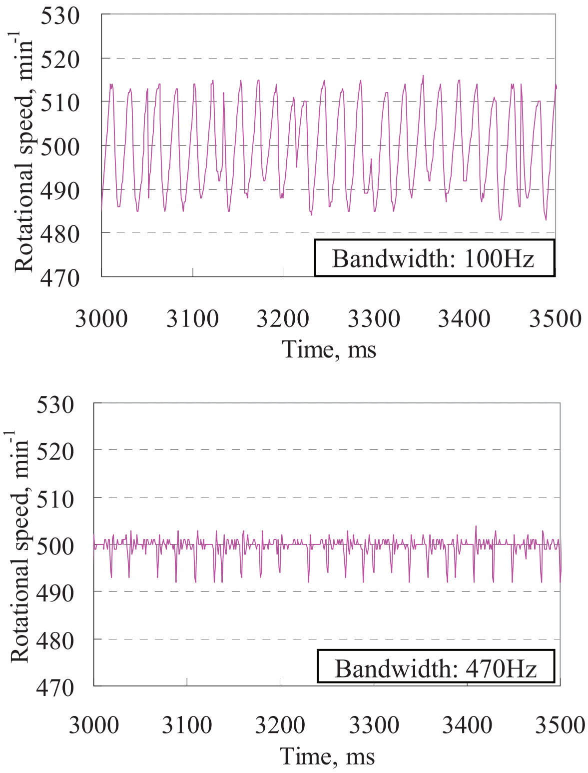

Fig. 6. Rotational speed comparison of PMSM.

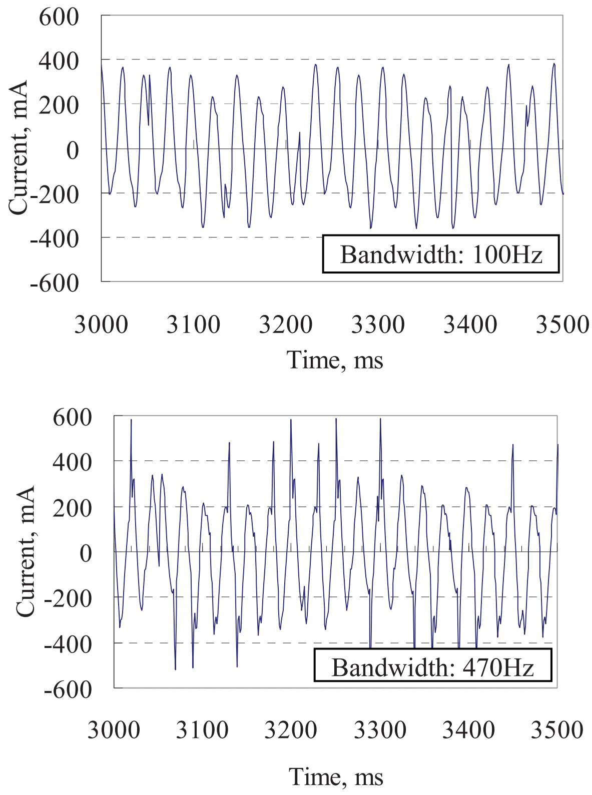

Fig. 7. Motor current comparison of PMSM.

Considering that the maximum bandwidth of the PMSM motor is 470 Hz, six different bandwidths, 50, 75 100, 200, 300, and 470 Hz, were tried by changing the velocity gain to observe the effect on tool wear. Fig. 5 shows a Bode plot of the PMSM after tuning the controller to have a 100Hz bandwidth, which is similar to the bandwidth of the induction motor introduced in section 2.

Fig. 6 shows the spindle rotational speed during the milling process. As shown in the figure, rotational speed largely fluctuates when the bandwidth of the PMSM is set to 100 Hz whereas the speed is very stable for the 470 Hz bandwidth. It is obvious that a higher bandwidth is preferable in terms of spindle rotational speed because change in rotational speed represents fluctuating feed per tooth and cutting forces in the midst of the material removal process.

In contrast, the motor current shown in Fig. 7 ranges $\pm$350 A for the 100 Hz bandwidth, and the peak current of the 470 Hz bandwidth is much higher than that of 100 Hz. It is commonly known that the torque of a PMSM is proportional to the current. Thus, it can be observed that the torque right after the cutter engages the workpiece becomes higher as the bandwidth of the motor becomes higher. This implies that the spindle gives extra stress on the cutting edges and consumes more cutting energy, which is not preferable for cutting edges.

A tool wear test has also conducted to investigate the effects of the spindle rotational dynamic behavior on the tool life in this specific milling application. Fig. 8 shows flank wear V_B of the cutter obtained at various bandwidth settings. Similar to the past studies [5, 6], by changing motor dynamics, the tool wear characteristics changed. Fig. 9 also shows the cutting edges after machining. It is interesting to notice that the lowest flank wear V_B was obtained when machined with the 100Hz bandwidth, and the highest and lowest bandwidths resulted in higher damage on the cutting edge. Although a cutting process is a very complicated process, it is clear that the spindle rotational dynamics affect the process and influences the cutting results, such as tool wear. For the cutting experiment, it was found that a bandwidth of 100 Hz for the PMSM spindle results in minimized tool damage.

However, it is important to emphasize that different optimum parameters should exist for different milling applications. There are many possible practical applications utilizing the flexible spindle motor control. The spindle dynamics can be optimized for to meet the milling requirements, such as tool life, surface integrity, and vibration. For instance, one of the main interests for the die and mold industry is the surface quality of their final products. Thus, the spindle can be tuned to achieve the best possible stable rotation to achieve stable feed per tooth during the milling operations for the best surface quality. The motor dynamics can also be optimized in order to minimize vibrations during cutting operations. Different machine tools have different dynamics. Heavy duty machines are usually very rigid and high speed machines sometimes sacrifice rigidity for high speed operations. The spindle sometimes can simply be adjusted to damp out the vibration, or it can also be precisely tuned by taking into account machine dynamics to balance the entire machine tool dynamics, including machine structure and servo drives.

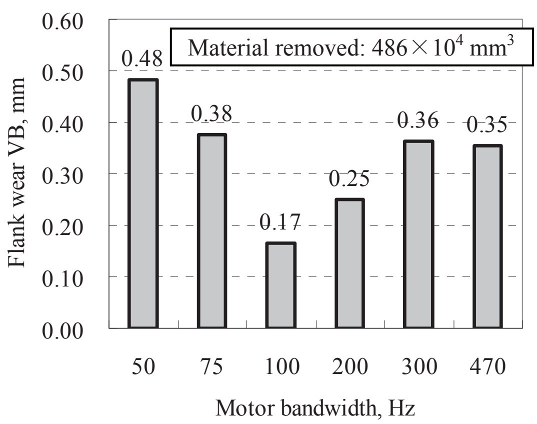

Fig. 8. Effect of spindle motor bandwidth on flank wear.

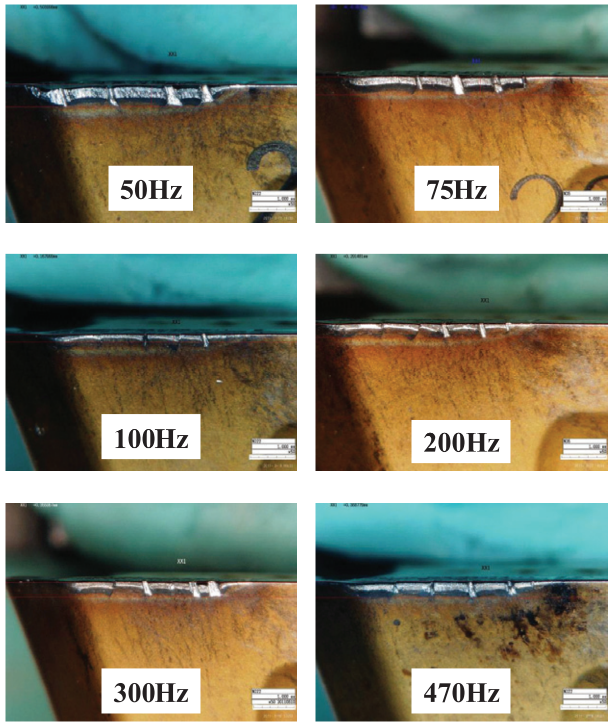

Fig. 9. Flank faces of the tools after milling with a various bandwidth.

5. Conclusion

In order to find the effect of dynamic characteristic of a milling spindle in the rotational direction, this paper introduced the concept of the flexible rotational rigidity control by software using the high performance PMSM. By conducting theoretical and experimental studies, the following conclusions have been obtained in this paper:

- It is important to design a high bandwidth milling spindle for the flexible motor control in order to meet a wide variety of cutting needs.
- Different kinds of dynamic characteristics can be easily achieved by software control of the high bandwidth PMSM. The compensator model was introduced to change the spindle motor characteristics
- The same dynamic characteristics of an induction motor can be achieved with the PMSM by applying the compensator model.
- Dynamic characteristics of the spindle are shown to affect cutting processes and change tool life patterns.
- By optimizing software parameters of the controller in the milling spindle motor, tool life optimization is also possible.
- The optimal spindle setting was found for the cutting experiments tried.
- A wide variety of applications adopting the flexible motor control have been introduced.

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